

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

TITLE: METHOD AND APPARATUS FOR PROVIDING PARALLEL EXECUTION OF COMPUTING TASKS IN HETEROGENEOUS COMPUTING ENVIRONMENTS USING AUTONOMOUS MOBILE AGENTS

5

INVENTOR: MARC SCHNEIDERMAN

SPECIFICATION

10

BACKGROUND OF THE INVENTIONField of the Invention

The present invention relates to a method and apparatus for providing parallel execution of computing tasks in heterogeneous computing environments using autonomous mobile agents.

15 More specifically, the invention allows a multitude of computing tasks to be broken down into smaller tasks, distributed across a variety of nodes, and computed in parallel by such nodes. Computing tasks can be distributed to a plurality of nodes by self-migrating, autonomous mobile agents that are capable of carrying state information from one host to another host. Execution of computing tasks can be interrupted at a first host and transferred to a second host, where 20 execution can then be seamlessly completed. The invention provides a means for collaborating the agents in real time, facility monitoring means for the agents, debugging means for allowing realistic thread migration of the agents, and dispatching means capable of breaking down given computing tasks into smaller tasks to be executed by a plurality of agents simultaneously executed across heterogenous, networked computing environments.

25

Related Art

Since the dawn of the computer age, scientists, academic researchers, engineers and programmers have attempted to design, develop, and refine systems to provide increasingly optimized uses of available computing resources. While attempting to achieve these goals, such efforts have sought to continually lower the overall cost of each mathematical or logical instruction executed within a program. Ultimately, these endeavors sought to create a computer program and/or system that was more reliable and less subject to network failures.

10 In the 1970's, remote procedure calls gained acceptance in the IBM mainframe environment. This was the result of improved communications technologies and protocols that enabled a secondary computer system to invoke a program written and executed on an IBM mainframe host, and to return the results of computation to the secondary computer.

15 In the late 1980's, the concept of client/server computing gained popularity, and in a broad sense, supported the notion of remote programming. This technique, whereby a set of instructions could be passed to a server for execution thereon, created a new architecture based upon a two tier computing model. One example of this is a Structured Query Language ("SQL") statement that can be created on one computer and then executed by a remote server. Typically, 20 the SQL code is created via a graphical user interface located at the client.

In the 1990's, a major shift in programming paradigms occurred. The structure of computer programs began to move from the traditional procedural model to object-oriented

models. Additionally, there was a renewed vigor to develop distributed computing technologies that would allow computer programs to be broken up and executed across two or more machines connected via a network.

5 Companies such as Microsoft, Sun Microsystems, and Visigenics have produced products, language facilities, and operating system enhancements that allow an object residing on one machine on a computer network to remotely call the methods within another object located on a second computer system. Microsoft's technology, Distributed Component Object Model ("DCOM"), was originally proprietary and could only be used within the Windows® environment. Sun Microsystems created two new programming API's for its Java® programming language, namely Remote Method Invocation ("RMI") and Enterprise Java Beans ("EJB"). Visigenic implemented specifications set forth by the Object Management Group ("OMG") to provide a distributed computing technology called Common Object Request Broker Architecture ("CORBA").

15 All of the above technologies required remote objects to be installed on the computer systems where such technologies were to be run. Additionally, variation of client-side stubs and server-side skeletons was required to effectuate the marshalling and unmarshalling of returned data and parameter values. Accordingly, the limitations and shortcomings inherent in the above 20 technologies have precipitated the need to create object-oriented software programs that can transport themselves from one machine to another without requiring a user to install software on the remote computers and without requiring any modification of virtual machines residing

thereon. Further, the need arises for such programs to traverse a heterogeneous network of computing devices that may be connected via potentially unreliable communication channels.

To date, organizations undertaking the monumental challenge of developing and introducing mobile agent technologies to address the above needs have achieved very limited success. This is due to both the radical shift in computing paradigms inherent in distributed computing and a lack of viable architectural designs and methodologies. Some of the more notable projects in the academic realm pertaining to mobile agent technologies include “Agent TCL” developed at Dartmouth and Tacoma developed at Cornell University. In the corporate realm there are such products as IBM’s Aglet workbench, Mitsubishi’s Concordia, and General Magic’s Telescript/Oddessy. As noted earlier, however, such products fail to address the need to provide easily transportable mobile agents that function efficiently in heterogeneous computing environments.

An additional need exists in the mobile agent technology realm; namely, the need to provide mobile agents that support real-time thread migration. Prior to the present invention, only mobile agent systems written in languages other than Java, such as TCL or Telescript, could support thread migration. In the late 1990’s, thread migration using the Java programming language could be achieved only by modifying the virtual machine itself, which severely reduced the attractiveness of a mobile agent product by requiring a proprietary Java virtual machine. The present invention, by contrast, provides realistic thread migration using a standard, off-the-shelf Java Virtual machine, without requiring the modification of the virtual machine or the creation of a proprietary virtual machine.

None of the previous efforts of others, either alone or in combination, disclose or teach the benefits of the method and apparatus of the present invention for providing parallel execution of computing tasks in heterogeneous computing environments using autonomous mobile agents, 5 nor do they teach or suggest all of the elements thereof.

OBJECTS AND SUMMARY OF THE INVENTION

It is a primary object of the present invention to provide for improved distributed computing over a plurality of computing systems.

5

It is another object of the present invention to provide for improved parallel processing of computing tasks over a variety of distributed computing systems.

It is yet another object of the present invention to provide for improved processing of computing tasks by a plurality of computing systems regardless of the underlying operating systems and hardware of such computing systems.

10

It is still another object of the present invention to provide an improved distributed computing system wherein computing tasks are accomplished by a plurality of virtual machines residing in nodes connected to the distributed computing system, without requiring a user to install software at the nodes or to modify the virtual machines.

15

It is another object of the present invention to provide a collaboration environment wherein a plurality of mobile agents can communicate with each other in real time.

20

It is also an object of the present invention to provide a dispatching system wherein complex computational tasks are broken down into smaller computational tasks and distributed to a plurality of computing systems using mobile agents.

It is yet another object of present invention to provide a monitoring system wherein status information corresponding to mobile agents can be recorded and monitored.

5 It is a further object of the present invention to provide a debugging system for a computing host wherein the execution stack for running mobile agents can be maintained, reconstructed, and traced.

10 It is still another object of the present invention to provide improved thread migration for mobile agents, wherein a plurality of mobile agents can be migrated from one computing system to another and withstand interrupted execution.

15 It is yet an additional object of the present invention to provide improved thread migration without requiring a user to install software at a plurality of computing nodes or to modify virtual machines located therein.

It is an object of the present invention to provide improved dynamic distribution of mobile agent processing code from a web server to plurality of client virtual machines so that mobile agents can be executed on clients not having mobile agent processing code.

20

A method and apparatus is provided for breaking down computing tasks within a larger application and distributing such tasks across a network of heterogeneous computers for simultaneous execution. The heterogeneous computers may be connected across a wide or local

area network. The invention uses mobile agents that can be self-migrating and can transport real-time state information as they move from one host to another, thereby allowing for continued execution where the mobile agents may have left off. The invention includes a server component for providing an execution environment for the agents, in addition to sub-components for handling real-time collaboration between the mobile agents and providing facilities monitoring during execution. A dispatcher that facilitates the break down of a complex computational task into smaller, more optimized parts is provided. Execution code can be dynamically transferred to remote nodes so that the mobile agents can execute in virtual machines located therein, without requiring modification to the virtual machines.

10 Additional components provide realistic thread migration and a collaboration environment for the mobile agents. Realistic thread migration is provided through the storage and later serialization of state information and execution stack trace information prior to migration of an agent from one host to a secondary host. The state information and execution stack trace information is then utilized by the secondary host to reconstruct the agent's state of execution prior to migration to the secondary host, so that seamless execution of the agent can be achieved across more than one host.

15 A collaboration environment allows the mobile agents to exchange data and messages while executing. Conference rooms provide a virtual workspace for the mobile agents, and a registration subsystem selectively assigns the mobile agents to the conference rooms. The conference room monitors and moderates communication between the mobile agents, also allowing them to share results of computations.

BRIEF DESCRIPTION OF THE DRAWINGS

Other important objects and features of the present invention will be apparent from the following Detailed Description of the Invention, taken in connection with the accompanying drawings wherein like reference numerals refer to like parts, in which:

FIG. 1 is a diagram showing system architecture of the present invention.

FIG. 2a is a diagram showing the agent console monitor of the present invention.

FIG. 2b is a diagram showing the agent dispatcher of the present invention.

FIG. 3a is a diagram showing an end note agent server of the present invention.

FIG. 3b is a diagram showing the mobile agent factory of the present invention.

FIG. 3c is a diagram showing the agent collaborator of the present invention.

FIG. 3d is a diagram showing an intermediate node of the agent server of the present invention.

FIG. 3e is a diagram of the agent debugger of the present invention.

5 **FIG. 4** is a hierarchical diagram showing the user interface for management consoles of the present invention.

10 **FIG. 4a** is a diagram showing log file formats of the present invention.

15 **FIG. 5** is a flowchart showing initialization of the agent server of the present invention.

20 **FIG. 6** is a flowchart showing client connection acceptance procedures of the agent server of the present invention.

25 **FIG. 7** is a flowchart showing generic processing of agent messages containing RMI requests by the agent server of the present invention.

30 **FIG. 8** is a flowchart showing generic server processing of an agent message RMI request.

35 **FIG. 9** is a flowchart showing the custom class loader of the present invention.

40 **FIG. 10** is a flowchart showing agent server processes for handling RMI requests to obtain lists of running agents.

45 **FIG. 11** is a flowchart showing management console registration processes.

FIGS. 12, 13, 14 are flowcharts showing generic processing of a request to launch a mobile agent.

FIG. 15 is a flowchart showing generic processing of a request to launch a mobile agent
5 notifying the management console and dispatcher.

FIG. 16 is a flowchart showing processes for creating an agent object.

FIG. 17 is a flowchart showing processes for creating an agent dispatcher.

FIG. 18 is a flowchart showing processes for sequencing remote agents.

FIG. 19 is a flowchart showing processes for launching an agent and obtaining a result.

15 FIG. 20 is a flowchart showing processes for receiving results from a mobile agent that has just complete processing on a remote machine.

FIG. 21 is a flowchart showing processes for running the agent monitoring console.

20 FIG. 22 is a flowchart showing processes for registering the agent console model with remote servers.

FIG. 23 is a flowchart showing processes for sending an RMI request to a remote server.

FIGS. 24, 25 are a flowchart showing processes for obtaining a list of running servers and building a tree node data representation model.

5 FIG. 26 is a flowchart showing management console processes for receiving messages indicating that an agent process has started on a remote server.

10 FIG. 27 is a flowchart showing management console processes for receiving messages indicating that an agent process has completed on a remote server.

15 FIG. 28 is a flowchart showing processes for determining network latency.

FIG. 29 is a flowchart showing processes for determining server availability that are executed on a remote server.

FIG. 30 is a flowchart showing processes for launching an agent debugger.

FIG. 31 is a flowchart showing processes for handling receipt of agent debugger events.

20 FIG. 32 is a flowchart showing processes for migrating and running autonomous mobile agents using an execution stack.

FIG. 33 is a flowchart showing processes for migrating and running autonomous mobile agents when either a first server on itinerary or execution stack is unavailable.

FIG. 34 is a flowchart showing the agent collaboration subsystem of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The methodologies, software components, architecture, and flowcharts of the present invention constitute a complete system that is capable of systematic breakdown of a 5 computationally intensive task into smaller parts for distribution across a network. In addition, the invention provides autonomous mobile agents that have the ability to migrate freely across a network of computers having a multitude of operating systems. The entire system of the present invention can be executed using a plurality of commercially-available virtual machines residing in remote computer systems, without requiring modification by the user of such virtual 10 machines.

To assist the reader, the following glossary of terms used in this document is provided.

The definitions in this glossary are not exhaustive and are not to be used to limit the scope of the present invention.

Glossary of Terms

AddObserver() Method: a function within the standard Java Observable class which allows for the addition of Observer objects.

Admin class: a proprietary class that contains methods to perform administrative tasks such as registering a management console.

Agent: A computer program that acts on behalf of a user or set of data or instructions provided by the user.

Autonomous Mobile Agent: An agent that is not bound to the system where it originates, and is capable of transporting itself from one machine to another machine residing on a network.

Bytecodes: A compiled version of instructions written in the Java programming language.

Class: An association of objects, data, and procedures commonly known in the object-oriented programming art.

ClassLoader: a standard Java abstract class that can be used to define policies for loading Java classes into a runtime environment.

Class Loading Mechanism: a facility that provides desired functionality for specific policies within an implementation of the ClassLoader class.

ClassNotFoundException: a standard Java exception created when a class loader is unable to load a specified class.

DefaultMutableTreeNode: a general-purpose node in a tree data structure, which may have at most one parent and zero or more children. DefaultMutableTreeNode provides operations for examining and modifying a node's parent and children, in addition to operations for examining the tree to which the node belongs. A node's tree is the set of all nodes that can be reached by starting at the node and following all possible links to parents and children. A node with no parent is the root of its tree; a node with no children is a leaf. A tree may consist of many subtrees, each node acting as the root for its own subtree.

10 **GetResults()**: a method within an AgentMessage class that retrieves the results of an RMI method call or the results of computation returned from a remotely-executing mobile agent.

15 **GetRunningAgentNames()**: a method within the Admin class that obtains a list of names representing agents currently running on an agent server.

15 **GoToWork()**: a method within the Agent class that is used to launch a mobile agent.

Instantiate: The process of creating an object to be used by a program.

20 **IOException**: a standard Java exception created when a runtime error occurs during an input or output stream operation performed on a file or socket connection.

Listening Thread: A computing process that waits for one or more actions to occur in a computing environment, and alerts another process when a desired action occurs. Often used to

describe a server-side component that waits for an incoming socket connection originating from a client initiating a request to submit.

LoadClass: a method within the ClassLoader class that loads a class using a policy 5 defined within the ClassLoader class.

MalformedURLException: a Java language exception created during the instantiation of a URL object if a parameter passed to the constructor of the object does not represent a valid URL.

10

NotifyObservers(): a method within the Java Observable class which notifies observers that a property of an observable object has changed.

15

Push stack event: a process by which the name of a method to be invoked and its associated parameters are placed on an execution stack.

20

Realistic Thread Migration: The process by which the current execution state of a mobile agent can be captured prior to migration of the agent across a network, and reconstructed at a remote server host when the agent has successfully relocated to the remote server host. Additionally, a process by which the simulated serialization of a thread and its movement between two distinct virtual machines, can be accomplished without modifying the runtime environment or using a programming language other than Java.

Remote Method Invocation (“RMI”): a process by which one program running on one machine can invoke a procedure within a program running on a secondary machine.

SetChanged(): a method within the Java Observable class that records changes in an observable object.

Skeleton: A server-side implementation of a stub.

SocketException: a Java language exception created when a socket connection cannot be established.

Stack trace: A set of function calls and the parameters passed to them which are invoked as a computer program executes and organized in the chronological sequence in which they are called; also referred to as “execution stack trace.”

State Information: Information regarding the execution status of a mobile agent.

Stub: A client-side software component, oftentimes automatically generated by a distributed computing tool, which handles the marshalling and unmarshalling of data through a socket connection when communicating to a remotely-deployed object.

Swing Components: Components within the Java programming language that allow a programmer to implement Graphical User Interface (“GUI”) components such as buttons, lists, menus, and text areas.

5 **Thread:** A single sequential flow of control within a computing process. The process may have multiple, concurrently executing threads.

10 **Thread Migration:** The capability of a mobile agent, in the midst of execution, to transport itself from one server node to another, and upon arrival at the secondary node, to continue executing at the point at which it left off.

15 **Update():** a Java language construct that denotes a named method within a class for receiving incoming events that are initiated or delivered from other components within a system.

20 **Virtual Machine:** A program that operates as a separate computing environment, may be implemented across a variety of hardware and software architectures, and is capable of executing instructions written in a programming language.

A preferred embodiment of the present invention comprises a number of agent servers interconnected via a TCP/IP network, wherein there are two distinct types of servers. The first type is designed to be an intermediary that can participate in the actual launching or migration of agents onto other specified servers. The second type is an end node that is capable of receiving

and executing agents, but is not capable of launching or migrating agents. Both servers provide an environment in which autonomous mobile agents may be independently executed.

The agent servers function as software building blocks that allow the creation of additional, highly-specific system components. An agent dispatcher subsystem that breaks down computationally intensive tasks is built upon an agent server. This subsystem is responsible for breaking down a computing task, identifying appropriate agent servers, launching the agents and processing or reassembling the intermediate results. An agent monitor, which includes a management display console, is built on top of an agent server. The display console visually depicts those machines working as agent servers within the system. Additionally, the console visually displays agents as they initialize, begin execution, run, and stop execution, in real-time. In a preferred embodiment of the invention, the console is implemented as a Java application having a user interface developed with Swing components.

Two integral subsystems of the invention that are not built into the agent server but form part of the invention are the agent collaborator and agent debugger. The agent collaborator works as a virtual meeting room in which information can be shared between all of the executing mobile agents in attendance. The agent debugger monitors the execution of all active agent processes running on a specific host. It automatically stores a complete stack trace of all executing agents in real-time. The debugger may or may not reside on the same host as the agents it monitors. The facilities available as a result of the agent debugger allow for realistic thread migration, whereby an agent can migrate from one host to another and begin execution in

a new environment at virtually the same point where the agent terminated execution prior to migration.

An industry-standard component utilized by the present invention is a standard web server which utilizes the Hypertext Transfer Protocol (“HTTP”) to transfer data. The web server, in an embodiment of the invention, is used as a storage facility for mobile agent classes. Via a network-aware class loading mechanism, bytecodes for any mobile agent or dependent class can be downloaded to a local agent server from the closest or least-used web server. This approach significantly reduces network traffic and agent travel times, as opposed to other approaches contemplated in the art.

The present invention implements a proprietary, lightweight, and highly portable form of RMI that is used internally by the system but can also be used by those who create software programs with the present invention. The most common implementations of RMI known in the art require the creation of related classes known as “stubs” and “skeletons.” These classes, which are usually generated by an automated tool, handle low-level socket communications. Additionally, they provide for the marshalling and unmarshalling of requests made from the client to the server. The most common RMI-related implementations in the art require a universal name space, such as Java’s JNDI. Importantly, the implementation of RMI achieved by the present invention does not require the creation of stubs and skeletons, nor is any type of object discovery service required.

Referring to the accompanying drawings, in which like reference numerals refer to like parts, **FIG. 1** is a system-level diagram of the present invention. Agent dispatcher **1** breaks down a computationally-intensive task and then distributes it in the form of mobile agents **22a**, **22b**, **22c**, **22d** to carry out a portion of the task. A network comprising one or more routers **3** and a plurality of hubs **4** connects a plurality of computer systems and can be based upon the TCP/IP protocol. Connected to hub **4** are one or more computer systems of various manufacture running different operating systems but all having a Java 1.1 or higher virtual machine installed and available.

10 All mobile agents run within an environment known as an “agent server” of which there are two types, end node **18** and intermediate node **6**. An agent server, agent console, agent collaborator, and agent dispatcher can operate on any computer system **7** presently known in the art and capable of supporting a Java virtual machine bearing version numbers 1.1 or higher.

15 Built upon the agent servers are other, more complex subsystems. Agent dispatcher **1**, described above, breaks down a computing task into smaller parts for simultaneous execution. Additionally, agent console **2** provides a real time management display as the agents traverse the network. Agent collaborator **16** provides the agents with a place to meet and exchange information, regardless of where the agent is located on the network.

20 Agent debugger **5** stores the stack traces of agents as they execute within the agent server environment. This subsystem provides a major technological advantage, namely realistic thread migration. Prior to the present invention, all Java-based mobile agent systems seeking to provide

thread migration had to implement custom modifications to the virtual machine in order to do so. Significantly, the present invention provides such thread migration without requiring modifications to the underlying virtual machine.

5 Web server **14** is used to store the compiled bytecodes of the mobile agents. The agent servers make HTTP calls to the web server to download the bytecodes as necessary. Web server **14** transfers compiled bytecodes **20** to any mobile agents executing on remote systems and requiring such bytecodes for remote execution. Importantly, web server **14** allows compiled bytecodes **20** to be downloaded using a customized class loading mechanism and the industry-
10 standard HTTP protocol.

FIG. 2a represents the architecture of agent console **2** of the present invention. Within this subsystem there are several core subcomponents. Console model **42**, which holds all data representing running servers and agents, is a complex, tree-like data structure loosely based on an acyclical redundancy graph. Console controller **44** is the subsystem's connection to the outside world, through which it registers itself with all active servers and receives messages containing status updates. Console view **46** is a graphical user interface for the management console. Helper class **48** performs background tasks such as acquiring a list of running servers. Agent server end node **18** provides an appropriate execution environment for mobile agents and
15 is described in more detail in FIG. 3a.

FIG. 2b is a diagram of agent dispatcher **1** of the present invention. Sequencing facility **66** is responsible for the programmatic breakdown of a computation into smaller sub-components

embodied as agents. Agent dispatcher 1 also assigns a sequence in which to launch the mobile agents. Agent launcher component 64 identifies and prepares all of the agents that need to be transported to remote server nodes. After preparation, each agent is then launched in turn. Results processing subsystem 68 receives the product of the computations as they execute on any number of remote nodes, caches, and then assembles the intermediary processes into a final result. Agent dispatcher 1 is built upon agent server intermediary node 6, described in detail in

FIG. 3d.

FIG. 3a is a diagram showing agent server end node 18 of the present invention.

10 Computer hardware 34 represents any type of computer hardware known in the art. Operating system 36 represents any operating system known in the art that is capable of supporting a Java 1.1 or higher virtual machine 38. Server core 78 creates and manages listening threads, retrieves default values from property files, and handles the underlying socket-level communications between the server and its client. Server core 78 utilizes default deserialization procedures 15 inherent in the Java programming language to create objects from bytestreams read from socket connections. Mobile agent factory 80 is an object that manufactures new agents locally after first gathering initialization criteria from message objects passed to the server from a connected client residing anywhere on the network.

20 Listening threads 82, 84, 86, 88 contain logic to receive and process either an agent message or a mobile agent instance that has migrated from a remote server. It is to be understood that additional listening threads can exist, depending upon the number of entries in a disk based properties file. Encapsulated within listening threads 82, 84, 86, 88 are pieces of

information indicating whether a mobile agent should be manufactured or a local method should be invoked. In response to the pieces of information, the server pools the listening threads. In the pool, each thread sits idle while awaiting a connection request. When the connection is accepted, a thread is removed from the waiting pool and allowed to process the request. Upon completing this task, the thread is returned to the waiting pool.

FIG. 3b depicts the mobile agent factory **80** of the present invention. Mobile agent factory **80** dynamically creates agents and relies upon Java's base API's built into the "Class" object to create new classes **100, 98**, instantiating them on demand. Network based class loader **92** can easily and efficiently download agent class files in the form of Java bytecodes from any standard web server residing on the network. In a preferred embodiment of the invention, multiple web servers **96** may exist on the network, such that agent servers can download bytecodes from the nearest web server, thus significantly relieving network traffic. Network class loader contains an HTTP requestor **94** that simulates a "GET" request to web server **96** in a fashion similar to a normal web browser.

FIG. 3c represents the architecture of agent collaborator **16** of the present invention. Computer hardware **34** may be of any manufacture, running any native operating system **36**. Computer hardware **34** has an installed Java virtual machine **38**, version 1.1 or later. A Java Virtual Machine having a version of 1.1 or higher is required because the present invention utilizes functionality of the Java language that appears only in versions 1.1 or higher. It is to be understood that the present invention is equally compatible with versions of the Java programming language having version numbers higher than 1.1.

The server core **62** is of the same design as an agent server. Registration subsystem **73** handles all of the live connections with agents, no matter where they are located within the network. Additionally, registration subsystem **73** also informs the agents of all active 5 conferences occurring in real time.

Conference rooms **72** provide a virtual workspace in which one or more agents can collaborate and share information, including partial or complete results from computations. This component is responsible for starting, stopping, monitoring and or moderating all conference 10 proceedings. In conference rooms **72**, agents from any part of the system can meet in a virtual environment without ever having to physically reside on the same computer system. Instant messenger component **71** allows two agents to establish a private channel of communications between themselves at any point in time. This approach allows one agent to communicate with another agent located anywhere on the network. The agent being contacted has the ability to 15 accept or decline.

Message delivery subsystem **74** is responsible for ensuring that all data and communications by one or more collaborating agents is both transmitted and received by the appropriate parties. Message delivery can be guaranteed if necessary. In an embodiment of the 20 invention, a standard message queue allows all messages to be placed on the queue and then read and removed by those with the correct permission. Other guaranteed communications methodologies supported by the invention are “publish” and “subscribe.” With this approach,

one agent registers itself as a listener requesting all messages for a certain topic. Another agent can register itself as a publisher, providing content relating to one or more established topics.

FIG. 3d represents an agent server intermediary node **6**. Agent server intermediary node

5 **6** comprises all of the components of agent server end node **18**, described above. Additionally, agent server intermediary node **6** is further comprised of a network latency and connectivity subsystem **58**, in addition to remote processor availability module **56**. Network latency and connectivity subsystem **58** transmits sample data packets to secondary agent servers determined to be active at predefined intervals using the commonly known TCP/IP “ping” utility. Network 10 latency and connectivity subsystem **58** then notes the amount of time elapsed prior to a response. Based upon an algorithm defined in **FIG. 28**, the server may be removed from the active server list. Remote processor availability module **56** monitors the state of the local processor and memory to determine system availability. It uses an algorithm detailed in **FIG. 29** to decide if the present processor’s resources and memory are sufficient to ensure a suitable execution 15 environment for migrating agents. Remote processor availability module **56** responds to processor status requests from other agent server intermediary nodes.

FIG. 3e is a diagram showing the agent debugger **5** of the present invention. Importantly,

agent debugger **5** provides realistic thread migration. Agent debugger **5** comprises standard 20 computer hardware **34**, native operating system **36**, and Java Virtual Machine **38**. Session manager **93** is a manager responsible for establishing and maintaining a connection with one or more agent servers. The agent servers may reside either on the same computer as the agent

debugger or at remote systems on the network. Request manager **83** is responsible for submitting monitoring requests to each of the agent servers to which that agent debugger **5** connects.

Object manager **85** tracks the creation of all mobile agent objects as they are instantiated and allowed to execute within the agent server environment. Event monitor component **87** receives events generated by the agent server environment. The events are filtered to allow only those events denoting the preparation of a class (object creation) as well as method entry points being reached. Class prepare events are passed on to object manager **85**, while events denoting method entry points being reached are passed to agent state machine **89**. Agent state machine **89** stores stack trace information for all running agents. When a method entry point event is reached and the name of the function is migrated, then agent state machine **89** determines that the agent needs to be transported to another remote server, with execution continuing at the point where it left off. Upon such transfer, the running agent is frozen, such that its currently executing thread is stopped. The agent is then serialized and moved to another remote host where information stored in agent state machine **89** is used to reconstruct the agent's previous state, so that execution may begin at the point at which it left off.

One embodiment of the present invention allows for the development of business application programs capable of transporting themselves, during execution while maintaining state, to alternative hosts. Such programs may reside on the same sub-net or anywhere on the Internet. Transportation of the programs may be triggered by abnormally high network traffic, possible computer hardware failure, or hostile attacks by computer hackers.

FIG. 4 is a diagram of screen layout graphically depicting all available servers within the present invention. The leftmost column **106** of the graphical interface represents the core components within the system. Listed in this column are component names, such as, “Servers,” “Debuggers,” and “Collaborators.” Through a mouse-driven graphical user interface, a user of the management console will be able to click on a small icon containing a plus sign **109** to the left of the component designation. This action will cause the selection to expand so that more detailed information for that particular component can be displayed.

Icon **107** to the left of leftmost column **106** in the diagram is depicted as having already been clicked by a user, so that detailed information for “Servers” is now displayed. The second column **108** displays more detailed information for a specific component. It is to be understood that second column **108** can display, but is not limited to, information about a plurality of components of the invention, such as server names, collaboration subsystem names, topics of conversation, and active debuggers. Last column **110** provides the user with the most finely-grained information about a given subsystem. For example, last column **110** could display the names of agents running on a given server, agents being monitored by the debugger, or agents involved in a given topic of conversation. As soon as an agent listed in last column **110** completes execution, it is removed from last column **110**.

FIG. 4a depicts the physical log file format used by the agent server of the present invention to store information in real time. The first field **111** stores the current date. The second field **112** stores the current time and is comprised of two-digit values corresponding to hours, minutes, seconds, and milliseconds. The third field **113** indicates whether the time is AM or PM.

The fourth field **114** is a three-character representation of the time zone. The fifth field **115** stores the name of the system component that is writing the log entry, for example “server.” The sixth field **116** represents the task that is presently being performed, such as agent creation or deletion. The seventh field **117** is a brief textual description of an event that has taken place. In a 5 preferred embodiment of the invention, an agent server logs all events on behalf of all other active servers.

FIG. 5 is a flowchart showing processes for initializing an agent server of the present invention. In step **120**, a disk-based properties file is read. Key values are extracted in step **122**, 10 such as the port number to listen to or the number of threads to place into a pool awaiting connection. In step **124**, an instance of the agent event monitor is created. An entry is then written into the physical log file in step **126** using the format described in **FIG. 4a**. At step **128** a decision point is reached. If an observer object is passed into the server’s constructor, then the observer member attribute of the agent server will be set in step **130**. This member attribute is set 15 by step **130** directly via a call to the `addObserver()` method within the ancestor. A server socket is then instantiated in step **134**. If failures are detected in step **136**, a stack trace is sent in step **138** to the standard out. Once a server socket is initiated by step **134**, a listening thread is created in step **140**, and then started in step **142**.

20 Upon completion, step **142** invokes step **144**, wherein the creation of a listening thread is logged. A decision is then made in step **146**. If the number of threads created is below a threshold determined by step **120**, step **146** re-invokes step **140**, where additional listening threads are created. If the listener threshold has been met, execution is completed in step **147**.

Importantly, the architecture of the server allows each listening thread that is spawned to share a reference to a single server socket. This allows a connection to be made from a pool of existing listeners, rather than by directly spawning a separate thread for each accepted client connection. This provides for a more stable, high-performance server, and eliminates the need for the Java virtual machine to constantly perform garbage collection on discarded connection threads. The term “garbage collection” is widely known within the object-oriented programming art, and refers generally to processes invoked by a virtual machine to free memory and other computing resources that are no longer being used.

10

FIG. 6 depicts a flow of events relating to an agent server accepting a client connection. In step **148**, the agent server waits for an incoming client connection. When the agent server accepts an incoming connection, a client socket is created in step **150**. Because there is a pool of listening threads, each of which may be busy, a connection request may remain in a pending state for a period of time, awaiting for a listening thread to be freed. Such a function is inherent in Java’s socket based libraries and not part of the present invention. In step **152**, the IP address of the client initiating the connection is obtained. Then in step **154**, the establishment of a connection is logged. In step **156** a socket input stream is acquired. From the socket input stream, an object input stream is created in step **158**. An attempt is then made in step **160** to read a serialized object. With this methodology, the invention takes full advantage of the standard object serialization methodologies inherent in the Java programming language.

FIG. 7 is a flowchart showing agent server processing of an agent message which contains an RMI request. An agent message in this system is a serializable object that passes information between servers. Such information may relate to many different processes described in various flows, and may include, but is not limited to, the identification of operations to carry out remotely, status information, completion, state information, and error-related data.

Beginning in step **166**, a failure is detected during the attempt to read a serialized object. If a failure is detected in step **166**, either an IOException **168** or a ClassNotFoundException **169** is caught. A stack trace is then sent to the standard output in step **170**. Then, the object input stream is closed in step **172**, and in step **174**, the socket input stream is closed.

If no exception is thrown while reading the serialized object, a decision point is reached. In step **176**, a test is performed to see if the object is an agent message. If it is, then step **178** is executed, wherein the command type and status of the agent are extracted. If the object is not an agent message, step **172** is executed. Once the command type and status of the agent are extracted in step **178**, another decision point is reached in step **180**, and a check is made to see if the message type is equal to “RMI.” If so, execution proceeds to step **182**, where the method to invoke and method parameters are obtained from the message.

FIG. 8 depicts a flow of events relating to invoking of a method within a server resulting from an RMI request from another server. In step **186**, an agent class loader is created. Then, in step **188**, a class identified within the agent message is loaded. Next, an array of class objects is instantiated in step **190** to hold all of the parameters that the method requires. A reference to the

actual method is then obtained in step 192. The method is finally invoked in step 194. At decision point 196 successful invocation of the method is determined. If the method was successfully invoked, then the return value from the call to the method is passed back in step 202. If the invocation failed, an exception is caught in step 198. The caught exception may be 5 one of many possible types, including the passage of an illegal argument, non-existence of the requested method within the specified object, or failure to create the object. If an exception is caught, the agent server in step 204 will create a specific instance of an agent exception. The newly-created agent exception will be placed within an array object and passed back to the calling method in step 206.

10

FIG. 9 is a flowchart showing a custom network-based class loading mechanism used by the present invention to dynamically load mobile agent class files from a standard web server located on a network. In step 206 an instance of an agent class loader is created, and is derived 15 from the ClassLoader class included in the Java language. In step 208, a check is performed to see if an instance of that class is stored in the cached hash table storing agents that have already executed on the machine. A decision point is then reached in step 210 to determine if an instance of the class is stored in the hash table. If so, then the instance is returned to the calling method in step 212. Alternatively, in step 214, the agent class loader then attempts to find the class locally on the machine on which it is running.

20

If the class is found in step 222, bytecodes are loaded from the local file system in step 216. The class is then resolved in step 218. During the process of resolving a class, the Java virtual machine will ascertain all of the dependent classes for the one currently being loaded. The

virtual machine will then automatically call the loadClass method within the agent class loader for all dependent classes.

If the class is not found in step 222, then an attempt is made in step 224 to establish an

5 HTTP connection to a web server containing the mobile agent and dependent class files. In step
226, the connection to the remote web server is opened for reading. Step 226 then invokes step
228, whereby the bytes representing the desired class are read via an input stream. The byte array
is then returned to the calling method in step 230, and in step 232, an array of bytes is converted
into a Java class object. In step 234, the class is resolved and a reference to it is placed in the
10 cached hash table of agents. Finally, in step 220 the class itself is returned to the calling method.

FIG. 10 is a flowchart showing the processing of an RMI request made to an agent server to obtain the names of all running agents on that machine. In step 238, the method getRunningAgentNames within the agent server admin object is called. That method in turn invokes a method in the event monitor object in step 240. Then, in step 242, a helper function returns an enumeration representing the keys of a hash table containing references to the actual agent threads that are running on the server machine. The enumeration of key values are the names of the running agents. The next step, 244, obtains the size of the running agent hash table and creates an empty string array. A decision is made in step 246 to determine whether the size
15 of the hash table is greater than zero. If the size of the hash table is greater than zero, then processing continues to step 250, where an array of Strings are dimensioned equal in size to the hash table. Then, the next available key from the enumeration is obtained in step 252. After obtaining the next available key from the enumeration, a value is set in the String array in step
20

254, representing the agent's name. Another decision point is then reached in step 256 to determine if more elements exist in the enumeration. If there are more keys, step 252 is re-invoked by step 256. If no more keys are available, then an array object containing the elements of the String array is created in step 258.

5

If, in step 246, the size of the hash table is determined to be equal to zero, then a String array with a dimension of one is created in step 248 and the value set to the word "none." After setting the value for this array step 248 then invokes step 258.

10 FIG. 11 depicts the processing of an RMI request to register the management console. In step 262 a method is called with the agent server admin object to register the management console. Next, an object event monitor instance is acquired in step 264. A method in the event monitor component is then called in step 266 to register a management console. In step 260 a check is performed to determine whether the previous call completed. If the call did complete, an array object containing a boolean value indicating the success or failure of the preceding operation is created in step 268. If the call did not complete, a check is performed in step 261 to see if an exception was thrown. If an exception was thrown, an array object is created in step 265, whose only member element is the thrown exception. If an exception was not thrown, a determination is made in step 263 as to whether the operation returned a null value. If so, then 15 an array object having a null member element is instantiated in step 267.

20 After the array object is created in either steps 268, 265, or 267, a new agent message is instantiated in step 270. The message object will be used to send back the result to the

management console. After this action takes place, the message type is set to “RMI” in step 272, and the command is set to “Response” in step 274. In step 276 a decision point is reached and a check is made to see if the first element in the array object is an exception. If so, step 276 invokes step 282, and the agent message status is set to “Failure Exception.” Alternatively, check 5 is made in step 278 to see if the first array element is null. If the first array element is null, then execution moves on to step 284, where the agent message status is set to “Null Exception.” If the result is negative for the decisions made in steps 276 and 278, then in step 280, the agent message status is set to “Success.” After the agent message status is set in either steps 280, 284, or 282, execution continues at step 286, where the results data attribute within the agent message 10 is set to the array object. Then, in step 285, an output stream is created from the server side socket. An object output stream is created in step 287, and in step 288, the serializable agent message is written to the object output stream.

FIG. 12 is a flowchart showing a server processing a request to launch a mobile agent. In 15 step 288 a test is made to see if the object read is an instance of an agent message. If the result is negative, a check is performed in step 294 to determine if an exception was thrown. If an exception was thrown, then the class not found exception is caught in step 292. The object input stream is closed in step 290 and in step 291 the input stream is closed. If the read object performed in step 288 returns an agent message, then processing continues to step 296, where the 20 message type, command, and status values are extracted. In step 298, a decision point is reached and a check is made to see if the message type is equal to “agent message” and command is equal to “request.” If these tests are both true, then step 300, retrieves the agent’s complete package name as well as its formal name.

In step 302, a new agent message is created which will be used to send a status response back to the remote calling process. Then, in step 304, the originating host value is set to the server's IP address or host name within the response. In step 306, the agent's formal name is set, 5 and in step 308, a mobile agent factory is created. In step 310, the create mobile agent facility is called within the factory object passing control to that method. Step 312 creates a new URL object. A test is made in step 314 to see if a MalformedURLException was thrown. If so, in step 318 it is caught and a new agent exception is created and thrown. If a MalformedURLException was not thrown, processing proceeds through the steps previously described in the detailed 10 explanation of **FIG. 9**. Upon returning, execution continues in step 320, wherein an initial instance of the class is created. If the creation of the mobile agent is determined to be successful in step 324, then execution continues as per the sequence of events described in below and depicted in **FIG. 13**.

15 **FIG. 13** is a flowchart showing further processes to launch a mobile agent. Sequence 13a begins with step 326 whereby the agent name is extracted, in addition to the method to invoke and parameters from the agent message sent by the dispatcher. In step 328 the initialize method of the mobile agent is called, passing to it the agent message sent by the dispatcher. Next the current host of the mobile agent is set to the IP address or machine name of the in step 330. Then 20 in step 332, the status of the output message to be returned is set to the dispatcher the agent created. In step 334, the originating host of the agent message is set to the IP address or machine name of the remote dispatcher. An event is logged in step 336, indicating that a mobile agent has been created. In step 338, the mobile agent's thread of execution is added to the hash table

containing all running agents. To complete the process, a check is performed in step 340 to see if the management console is registered on this server. If it is, program execution continues with sequence 14a in shown in FIG. 14; otherwise, sequence 14b in FIG. 14 is called.

5 Sequence 13b in FIG. 13 begins in step 342 by catching a class not found exception. Once this occurs a new agent exception is created and thrown in step 344. Processing continues in step 346 by sending back a message to the originating host that agent creation failed.

FIG. 14 is a flowchart showing continued processing for launching a new mobile agent.

10 Sequence 14a begins with the creation in step 342 of an agent object whose message type is “admin,” target host is the admin console, and command is “update.” Step 344 checks to see if the agent is ready to launch. If so, the next operation to execute is set, in step 346, from the agent’s origin host to this particular server. Next, in step 348, the agent name is set to that of the newly instantiated mobile agent. Also, in step 350, the agent status attribute is set to “Agent Created.” In step 352 an object output stream is obtained. In step 354 the agent message attribute of the agent object is set to the message that was created previously in step 302. The send server update method of the agent object is called, which in turn writes the message to the object output stream it establishes with the server running the console.

15

20 Sequence 14b, beginning in step 356, starts the mobile agent. In step 358 an event is written to the log file indicating that an agent is being started. Next, in step 359, the user-defined mobile agent process executes and completes. In step 360, the mobile agent calls the DispatchResults() method of its base class. It passes in as a parameter the computational results

of its efforts, which are then encapsulated as an Array object. In step 362, the mobile agent sets the values, within its agent message attribute, of command to “computation” and status to “result.” Execution then continues to step 364, where the mobile agent sets its runnable flag to “false.” In step 366, an event is written into the log file indicating that the agent has successfully completed. In the next step 368, a new agent object is created. Its underlying message type is set to “agent message” and the command is set to “computation.” In step 370, the status of the agent is set to “results.” Then, in step 372, the originating host value is set to either the server name or IP address on which it just executed. In step 374, the agent’s name is set to the name of the mobile agent that just completed execution. In step 376, the results attribute within the DispatchResults() method call, implemented within the abstract ancestor of the mobile agent, is expressly set to the Array object passed in as a parameter to the method call. In step 377, a handle to the event monitor is obtained. Finally, in step 378, a new agent utilities object is created. From that point on control passes to sequence 15a shown in FIG. 15.

15 **FIG. 15** is a flowchart showing the processing of a request to launch a mobile agent. Sequence 15a begins with step 382, wherein a new agent object is created, the message type is set to “administration message,” and the command is set to “update.” In step 384, the hostname is set to that of the management console. In step 386 the origination host is set to the server that spawned the mobile agent. Then, in step 388, the value for the name of the mobile agent that finished execution is set. In step 390 the status is set to “finished.” Step 390 then invokes step 20 392, wherein the agent message encapsulated within the agent object is written to the object output stream and is read at the server running the management console. After that process completes, another agent message contained within the agent object created in step 368 is written

to the object output stream in step **394**. This process sends a message to the agent dispatcher indicating that a specific mobile agent has successfully completed its task and has returned a result. Then, in step **396**, the server removes the completed mobile agent from the cached hash table of running agents. Its value is then set to null so that it may be garbage-collected by the 5 Java virtual machine in step **398**. Finally, the server thread, having completely finished processing, is returned into the free pool and waits another connection request from a remote server in step **400**.

FIG. 16 is a flowchart depicting the generic creation of an agent object. In step **402**, the 10 member attribute for the remote host is set to the value passed into the object when its constructor is called. Then, in step **404**, the default port number is obtained by reading a disk-based properties file. In step **406**, a new client side socket is created and connected to the host and port number specified. In step **408**, a decision point is reached, wherein a test is performed to see if an exception was thrown. If an exception was thrown, step **408** invokes steps **416** and **420**, 15 wherein the two most likely exceptions, IOException and SocketException, are caught. After the exceptions are caught they are written to the log file in step **422**. If an exception is not thrown, then processing continues in step **410**, where both an input and output stream is obtained from the opened socket. In step **412**, a new agent message object is created, the type is set to “agent message,” and the command set to “request.” Finally, in step **414**, a boolean flag is set to true, 20 indicating that the agent is ready to be launched.

FIG. 17 is a flowchart detailing the process of creating an agent dispatcher. The process begins at step **422**, wherein a new agent dispatcher implementation is instantiated. In step **424**,

an agent server is created and initialized in the manner depicted and described in **FIG. 5**. Then, in step **426**, the IP address of the local host running the agent dispatcher and server is obtained. In step **428**, a test is performed to determine if the IP address was successfully obtained. If an IP address was not successfully obtained, then execution proceeds to step **430** where an exception is 5 logged. If the IP address was obtained, then resource information is read from a properties file in step **432**. Then, in step **434**, a reference is obtained to an agent event monitor. In the following step **438**, the concrete agent dispatcher thread is started. Then, in step **440**, an instance of an agent utilities object is created.

10 In step **442**, a list of potential servers is obtained. In step **444**, actual process tasks that need to be carried out are identified. Then, in step **448**, the number of server tokens is counted. In step **450**, the next available token from the list is extracted. A decision point is reached and the token, which represents a server name, is compared to a null value in step **452**. In step **454**, a fully qualified Java package name is created for the agent server admin class. The following step, 15 **456**, sets the array to be used as the agent message parameter attribute to null. In step **458** an RMI request is sent to the remote server to check for process availability. When this call is made, the program on the initiating server running the agent dispatcher waits until a response is sent from the remote server indicating its availability. Sequences **29a** through **29b** are then invoked, the functioning of which are described in detail below. Once the response is received from the 20 remote server, execution continues at step **460** and the command value is extracted from the agent message read via the object input stream on the server running the agent dispatcher. A decision point is then reached in step **462**, and the command value is tested to see if it equals the response. If so, step **466** is invoked, wherein the status of the message is acquired. In step **468** a

test is performed to see if the status is equal to the server available. If the server is available, its name is added to the vector of operational servers in step 470, and then control continues at step 472, wherein another decision point determines whether there are more server tokens. If the server is not available, control passes to step 472. When no more server tokens are available, 5 then execution continues at step 474, in which the sequencing of remote agents takes place. Finally, agents are launched in step 476.

FIG. 18 is a flowchart showing the sequencing of remote agents prior to being launched.

Beginning in step 478, the number of tasks to be assigned is obtained. Then, in step 480, the 10 names of the corresponding mobile agents that need to be launched are obtained. In step 482 an array of mobile agent objects equal in size to the number of tasks to be assigned is dimensioned. In step 484, the list of available servers created through the reiteration of step 470 is cloned. The 15 next available server name is then determined in step 486. In step 490, the system performs a series of steps to ascertain network latency. These steps are described in detail in sequence 28a of **FIG. 28**. Upon returning from sequence 28a, a decision point is reached in step 488. A test is performed to see if the remote server is a level one, two or three network component. If the 20 server is one of these three, execution continues in step 492. If the server is not a level one, two, or three network component, control passes back to step 486. Assuming the server is a level one, two or three network component, an array for storing objects is created equal in size to the number of parameters that must be passed to the mobile agent. In step 496 the array is populated with objects to be used as parameters when the mobile agent is created on the remote machine. Following this action a new agent object is created in step 498. This agent identifies the specific 25 available server. The message type is set to “agent message” and command to “request.” in

sequence **16a**, described below. Upon returning from sequence **16a**, execution continues in step **500**, wherein the newly-instantiated agent object is inserted as the next element in the agent array dimensioned in step **482**. A new agent dispatcher information object is created in step **502**, wherein the agent's formal and package name is identified. Then, in step **504**, the IP address of
5 the dispatcher and the destination server are set in the dispatcher information object. In step **506**, the dispatcher information object is passed into the agent object created in step **498**. A test is then performed in step **508** to see if there are more tasks that need to be completed. If there are additional tasks, execution continues at step **486**; otherwise, a flag is set in step **510**, indicating that the sequencing of agents has been completed.

10

FIG. 19 is a flowchart showing processes within an agent dispatcher when launching a mobile agent. Beginning in step **512**, the next element in the previously sequenced array of agent objects created in step **482** is obtained. The `goToWork()` method is then invoked in step **514**. After this function completes, the agents obtains a reference to its object output stream in step
15 **516**. Program flow continues to step **518** where the agent message is written to the output stream. If an exception is thrown in step **520**, then a stack trace is sent to the standard output in step **522**. Alternatively, if the object is written successfully, program execution pauses in step **524** to wait for an agent message to be sent back by the remote server. When a response is received in step
20 **526**, execution continues. The message type and status of the command is obtained in step **528**. A decision point is then reached in step **530**. If the message type is equal to "agent message," the status set to "agent created," and the command value is equal to "response," then execution continues in step **532**. In step **532** the agent's boolean launch value is set to true. The agent's

running status is also set to true in step **534**. Finally, in step **536**, the remote agent is added to the hash table containing all running agents.

FIG. 20 is a flowchart showing processes for receiving at an agent dispatcher results sent back by a mobile agent. In step **538**, a decision is reached after an agent server running alongside the dispatcher accepts a socket connection and subsequently reads a serialized object, as previously described in step **160**. If the object is an instance of an agent message, control is given to step **540** wherein the message type, command, and status values are extracted. In step **542** a test is performed to see if the message type is equal to “Agent Message,” status is set to results, and the command value is “Computation.” If the test is positive then the `setChanged()` and `notifyObservers()` methods within the agent server module are executed in **544**. The agent server is derived from the `Observable` class. A class that implements the `Observer` interface automatically has its `update` method called by step **546**. In an embodiment of the present invention, the `Observer` is the agent dispatcher itself.

In step **548** the array result object is returned by calling `getResults()` with the agent message. In the next step, **550**, the length of the array of objects comprising the result is obtained. Next, a decision point is reached in step **552**. If the length of the array is greater than zero, execution continues at step **554**, wherein the result is extracted from the array object. Then, in step **556**, a decision point is reached wherein the result is checked to see if it is an instance of an exception or one of its subclasses. If the result meets these criteria, then a complete stack trace is sent to standard output in step **560**. An event is then logged in step **562**, indicating that the remote agent failed to complete its task and an exception was returned. In step **564**, another mobile agent is then launched on another available server to perform the same task as the

previous task which failed to complete, on another available server. If the result is not an exception, then it represents the computational outcome of the process of a remote mobile agent. Finally in step **558**, application-specific program logic is executed based upon and utilizing the results returned from all running agents.

5

FIG. 21 is a flowchart showing the process for initializing and launching an agent monitoring console. In step **564** an agent console view object is instantiated. This object will contain the graphical user interface for the system management components. In step **568**, a DefaultMutableTreeNode called “servers” is created. This object will serve as the root data structure containing leaves representing running agents. Next, a handle to the agent event monitor is obtained in step **566**. In the following step, **570**, the local host’s IP address is obtained. A decision point is reached in step **572**, wherein a check is made to see if an unknown exception was thrown. If an exception was thrown, processing continues in step **576**, at which point an error is written to the system event log. If no exception occurred, processing continues at step **578**, wherein an agent console model is instantiated. This object will serve as the data representation for most of the graphical elements displayed within the management console. In step **580** an agent console controller is created. This object serves as the link between the management console and the agents that are executing within the system. The console controller is the portion of the subsystem that receives messages from agents throughout the system as they are created, moved between servers, executed, and complete their assigned tasks.

After all of the above tasks have taken place, in step **582**, the internal tree model data member within the console controller is set to the console model created in step **578**. Then, the

console controller is added as a listener to events propagated by the console model in step **584**.

Execution continues in step **586**, where an agent server is created and started. In step **588**, a desktop pane is created. In step **590** the pane is set to be layered. After these tasks are completed

a reference to the root pane is then obtained in step **592**. Execution then proceeds to step **594**,

5 where a new window closing adapter is created. In the next step, **596**, the adapter created in the previous step is added as a window closing listener. A menu bar is created in step **598**, to which is attached a menu created in step **600**, and a number of menu items which are created in step **602**. Program flow continues with step **604**, where the title bar for the main window of the graphical interface is set to “Agent Management Console.” Following this event, a new menu item listener is created in step **606**. Finally, in step **608** the menu item listener created in the previous step is associated to each menu item.

FIG. 22 is a flowchart showing processes for registering the management console with remote servers. The flow of events begins with the creation of an agent console controller in step

15 **580**, as described above. During the creation of this object a number of steps are taken. The first step, **612**, obtains an instance of agent utilities. The second step, **614**, is to retrieve a list of all known servers. In step **618**, the next token is obtained from the list. A test is then performed in step **620** to determine whether the server’s domain name or IP address are null. If this test fails, execution will continue with step **622** where a string identifying the complete package name of

20 the agent server admin class is created. In step **624**, an array of objects is created for containing the parameters to be passed to the remote method. In step **626**, the first parameter is set to the IP address or domain name of the machine running the management console. Following this the second parameter is set in step **628** to the IP address or machine name of the remote agent server.

After parameters are set, an RMI request is sent to the remote server in step **630**. The method identified in the RMI request is RegisterManagementConsole. This call is a synchronous (blocking) call which will not return control back to the caller until the registration is completed on the remote server. When program control is returned, the array result object is extracted in step **632** from the message being returned. A decision point is then reached in step **634**, whereby the array result object is checked to see if it contains a Boolean object. If so, then control proceeds to step **636** in which the remote server is added to the list of active servers identified by the management console. Another decision point is then reached in step **638** a determination is made as to whether there are more server name tokens in the enumeration of known servers. If so, then execution loops back to step **618**. If the last server name token has already been processed, execution continues at step **640**. In step **640**, an enumeration of all running servers is created.

FIG. 23 is a flowchart showing processes for sending an RMI request from the agent management console to a remote server. In step **644**, a mobile agent object is created, the remote machine name or IP address is passed, the message type is identified as RMI, and the command is set to “request.” Then, in step **654**, a client socket is instantiated and opened for both read and write operations. If an exception is thrown in step **652**, execution proceeds to step **650** wherein an instance of the event monitor is obtained. Subsequently, the failure to connect to the remote host is logged in step **648**. A stack trace is then sent to the standard output in step **646**. If an exception is not thrown when creating the socket, then execution proceeds on to steps **656**, where an output and input stream are obtained from the open socket. Next, in step **658**, a new agent

message is created and the message type and command identified in step 644 is passed to the constructor.

Another test point is then reached in step 660. If the newly created agent is ready to 5 launch, the process continues with step 662, wherein the agent's remote object name is set. In step 664 the method to invoke remotely is set. Parameters for the remote method invocation are set in step 666 and the remote method is executed in step 668. In a preferred embodiment, the RMI call is a synchronous blocking call. When the RMI returns in step 670, an agent message is received from the remote server. Once the message is available, the message status is retrieved in 10 step 672. A decision point is then reached in step 674. If the status is equal to success then execution continues to step 678, wherein the Array result object is extracted from the returned message of step 670. If the status of the operation is not equal to success, the exception contained in the message object is extracted and the exception logged in step 676.

15 FIG. 24 is a flowchart processes for obtaining a list of running servers and building a tree node data model. This process is started by obtaining the next server name from the enumeration of currently running servers in step 682. In step 684, a new default mutable tree node representing the remote server is added to the existing root node which was created in step 568. Next, in step 688, a fully qualified package name is created for the agent server admin class. In 20 step 690, an RMI request to a remote server identifying the method getRunningAgentNames is called. The Array result object is then removed from the agent message sent back by the remote server in step 692. A decision point is then reached in step 694, whereby the result object is checked to determine if it equals a null value. If the result object's value is not equal to null,

execution continues in step 696, wherein the first agent's name is extracted from the result object. In step 698, the name is added to a vector built iteratively. Another test point is encountered in step 700, wherein the result object is examined to determine if it contains any additional agent names. If additional agent names exist, step 700 re-invokes step 696. If no 5 additional agent names exist, step 700 re-invokes step 702, wherein an enumeration of agent names is returned.

FIG. 25 is a flowchart showing continued processes for building a tree model of running servers and agents. In step 704, the next element of the enumeration containing agent names is 10 acquired. A decision point is reached in step 706, wherein the agent name is compared to the string “none.” If the result is true, then execution proceeds to step 708. In step 708, a new DefaultMutableTreeNode containing the name of the running agent is created. After this action is 15 complete, the agent node (leaf) is added in step 710 to the server node (branch) created in step 684. The last step in the process, step 712, checks to see if there are any remaining agent names in the enumeration. If so, step 712 re-invokes step 704. If no agent names exist in the enumeration, then the tree node data representation has been fully populated.

FIG. 26 is a flowchart showing processes for receiving at the management console 20 messages indicating an agent process has started on a remote server. Starting at 7a, at which point in time step 160 has completed successfully, a decision point is reached in step 712. In step 712, an object is read to determine if it is an instance of an agent message. If the object is an instance of an agent message, then processing continues with step 714, at which point the message type, command, and status values are extracted. In step 716, another test point is

encountered, whereby the message type is compared to “admin message” and the command compared to “update.” If both of these conditions are met, step 716 invokes step 718, whereby the observer object is tested to see if it is equal to null. The observer object represents the agent console controller created in step 580. If the value of the observer is not null, execution proceeds 5 to step 720, where the setChanged() method of the observable object is called. In step 722, the notifyObservers() method is called in the same agent server. This method automatically invokes the update() method within the agent console controller object in step 724. A test point is reached in step 726, whereby the object passed as a parameter to the update() method is checked to see if its type is an agent message. Under normal processing conditions, the object type is an agent 10 message.

Another decision point is then reached in step 728, wherein the status value from the message is tested to see if it equals “agent started.” If so, step 730 is invoked, at which point the given name of the mobile agent process running on the remote machine, in addition to the host 15 name, is extracted from the agent message. In addition, the IP address of the remote machine is also obtained from the message. In the step 734, the root DefaultMutableTreeNode, which is stored as member data within the agent console model, is retrieved. Thereafter, in step 736, an enumeration of the children of the root node is obtained. Step 738 cycles through all child nodes, each of which represents an agent server, and obtains their respective user object.

20

At step 740 a decision point is then reached. The user object, embodied as a String representing the name of the remote server, is compared to the server name obtained in step 730. If they are equal, execution continues to step 742, wherein a DefaultMutableTreeNode is created

using the name of the agent running on the remote server. Thereafter, in step 744, the current count for the number of child nodes that the agent server node contains is acquired. Finally the process is completed in step 746, wherein the node representing the remote agent is added to the server node as the very last object.

5

FIG. 27 is a flowchart showing processes for receiving a message at the management console indicating that a remote agent process has successfully completed. Beginning with step 748, a decision is invoked wherein the status of the message is checked to see if it equals “agent finished.” If true, execution continues at step 750 where the agent and remote server names are extracted from the incoming message. Then, in step 754, the root DefaultMutableTreeNode is obtained from within the agent console model. Processing continues to step 756, where an enumeration of children of the root node is obtained. The children represent the remote agent servers that are currently running. The next available element of the enumeration is then obtained in step 758. The user object is extracted from the child node element in step 760.

10

15

In step 762 a decision point is reached, wherein a test is made to determine if the remote server name is equal to the user object within the server node. If the result of this test is positive, then control proceeds to step 764, where an enumeration of server node children are obtained. Each child in this enumeration represents a running mobile agent. The next step, 766, retrieves 20 the next mobile agent node in the enumeration. Thereafter, the user object is obtained from that node in step 768. A decision point is then invoked in step 770 whereby the user object is compared to the name of the remote agent that has just finished running. If a positive comparison

is made, control passes on to step 772. In this final step the child node representing the agent is removed from the server node.

FIG. 28 is a flowchart showing processes for determining network latency. Beginning in

- 5 step **800**, a sequence of four data packets, each thirty-two bytes in length, is sent to a remote agent server. The remote server reads the data and sends it back to the originating host. During this latency period, the originating host waits for the packets to be returned or a timeout to occur in step **804**. A decision is reached, in step **816**, at which point a check is made on the originating host to see if one hundred percent (100%) of the data is returned. If all the data is not returned, 10 execution continues with step **826**. If all four packets are returned then execution continues at step **818**, wherein a check is made to see if the average elapsed time for the round trips made by the packets is less than ten milliseconds. If so, step **808** is invoked, wherein the remote server is identified as a level one component. If the result of the test in step **818** is false, then execution continues to step **820**, wherein the average elapsed time is compared to a period of one hundred milliseconds. If the elapsed time is less than one hundred milliseconds, the server is rated as a 15 level two component in step **810**. In step **822**, a decision is made as to whether the round trip time is between one hundred and one thousand milliseconds. If so, execution proceeds to step **812**, at which point the server is rated as a level three component. If the average elapsed time is greater than one thousand milliseconds, as ascertained in step **822**, then step **822** will invoke step 20 **832**. In step **832**, a test is performed to see if a third instance of latent response has occurred. If a third instance has not occurred, then control proceeds to step **814**, wherein the remote server is rated as a level four component.

If a third instance of a latent response has occurred, control is then passed to step **828**. Step **828** removes the remote server from the active and available list. If processing reaches the point where a server has been rated, execution continues with step **806** to determine if a periodic monitoring of the server is required. If periodic monitoring is required, this network latency 5 thread will halt for a system-defined period of time in step **802**. Upon awakening, the thread will once again ping the remote server as indicated in step **800**. If there is a data loss from the test performed in step **816**, execution continues with step **826**. A check is then performed to determine if a third instance of lost data has occurred. If so, then the server is removed from the active and available list in step **828**. Alternatively, control passes to step **802**, wherein the thread 10 is put to sleep for a pre-defined period of time.

FIG. 29 is a flowchart showing processes executed on a remote server for determining server availability. Beginning with step **840**, an availability request is received from an originating server. Then, in step **842**, the CPU utilization for the machine is ascertained. A 15 decision point is then reached in step **844**, wherein a test is made to determine whether CPU utilization is greater than fifty percent. If utilization is greater than fifty percent, an agent message is returned to the originating host in step **846**, indicating that there are not enough CPU cycles available. If the CPU is underutilized, step **856** is invoked, wherein memory availability is checked. Step **858** determines whether the available memory is greater than three-quarters of 20 total system memory. If so, execution continues to step **860**.

In step **860**, an agent message is returned to the originating server, indicating that the current processor is capable of running a mobile agent task. If the test performed in step **858**

fails, then decision point **864** is invoked. In step **864**, the available memory is compared to the total system memory. If the result is greater than fifty but less than seventy-five percent, another test is made in step **862**. In step **862**, total system memory is checked to determine whether same is greater than 256 megabytes of Random Access Memory (RAM). If the total RAM is greater than 256 megabytes, control is passed to step **860**, described above. If available memory is less than fifty percent of total system memory, then execution proceeds to another decision point. In step **866**, available memory is compared once again to the total system memory. If the available memory is not greater than one third of the system memory, a status message is sent back to the originating server in step **854**, indicating that the remote server does not have enough memory. If the available memory is greater than one third of the total system memory, a test is performed in step **852**. CPU utilization is again examined. If the utilization is more than twenty-five percent, a status message is returned to the originating host in step **848**, indicating that not enough resources are available on the targeted remote agent server. If CPU utilization is less than twenty-five percent, a message is returned to the originating host in step **860**, indicating that the remote server's process is currently available to run a mobile agent process.

FIG. 30 is a flowchart showing processes for launching an agent debugger of the present invention. Beginning in step **880**, a reference to the virtual machine manager is obtained from the bootstrap class. A corresponding list of attaching connectors is then obtained from the virtual machine manager in step **882**. In step **890** a single connector is removed from the list. Program flow then continues when a map of the connector's arguments and default values are obtained in step **894**. In step **898**, the value for the connector's port argument is obtained. Execution then continues to step **904**, wherein in which the agent debugger attaches to a running Java virtual

machine. In step 906 the agent debugger retrieves a reference to the virtual machine to which it has attached. Then, in step 908, it retrieves a reference to the event request manager. Upon retrieving the reference, the agent debugger obtains a reference to the event queue in step 902. The agent debugger then creates a new thread in step 900, which will sit and monitor the event 5 queue for incoming events. A class prepare request is then created in step 896. Next, the filter for the request is set such that the reference type equals autonomous mobile agent in step 892. The process continues with step 888, wherein a method entry request is created. Then, in step 886, the filter of the request is set such that the reference type is equal to autonomous mobile agent. Finally, the process completes in step 884, wherein both the class prepare and method entry 10 requests are enabled.

FIG. 31 is a flowchart showing agent debugger processes for receiving and acting in response to events. Beginning with step 920, the agent debugger's event monitor thread is configured to remain in an idle state while periodically reading from the queue. In step 926 an event set is received. Directly after this event is read a new thread to process the event is created in step 928. Following the instantiation of the thread, the thread is then started in step 930. In step 932, an event iterator object is used to gain access to the next available element in the event set. After extracting the next event, a decision point is reached in step 938. It is at this junction that the event is tested to see if it is an instance of a class prepare event. If the event is an 15 instance of a class prepare event, it is passed to the agent debugger object manager in step 950. Once this task completes, processing continues with the instantiation of a new agent digest object in step 952. Then, the newly created agent digest is forwarded to the agent debugger's state machine component in step 954. If the test performed in step 938 yields a false value, then program control passes onto step 940. In step 940 the event is checked to see if it is an instance 20

of a method entry event. If it is such an event type, then processing continues with step 942, where the name of the method is compared to “migrate.” If a negative comparison results, step 944 is invoked. Additionally, the method is examined to determine if it is a machine-dependent native method. If the method is not a machine-dependent method, a push stack event is created 5 and fired in step 946.

In step 948, the agent debugger state machine component receives the push stack event and dynamically modifies the agent’s logical stack in temporary storage. If step 944 determines that the method is a native method, execution is passed to step 936, at which point the system 10 queries the event iterator to determine whether there are any more events available for processing. If there are still events waiting, step 932 is re-invoked. If step 942 determines that the method name is “migrate” execution will continue with step 934. In step 934 the agent debugger will suspend the targeted mobile agent’s primary thread of execution on the remote host. In the next step, 924, the stack information contained within the debuggers state machine’s agent digest 15 is transferred to the newly-migrated autonomous mobile agent paused in the debuggee’s virtual machine. In the final step, 922, the agent debugger restarts the execution of the target mobile agent’s thread.

FIG. 32 is a flowchart showing the migration and initialization of an autonomous mobile 20 agent where the execution stack is available. In step 960, an autonomous mobile agent is instantiated on an agent intermediary server. Then, in step 962, the autonomous mobile agent’s thread of execution is created and started. The agent then carefully examines its itinerary in step 964. A decision point is then reached in step 976 and a check is made to see if this server is the

first one on its itinerary. If so, then execution continues to point **33a**, described in detail below and depicted in **FIG. 33**. If the server is not the first host visited, program flow continues to step **978**, at which point another decision is reached.

5 In step **978**, a check is made to determine whether execution stack information is available. If such information is not available, then execution continues at entry point **33a**, described in detail below and depicted in **FIG. 33**. If such information is available, step **980** is invoked, whereby the value of the restart variable is checked. In step **982** the value of the restart variable is evaluated and compared to “beginning.” If the result is true, step **994** is invoked, 10 wherein all of the stack frame elements are removed. Then, in step **995**, an iterator object is created and all of the available stack frame elements are placed into it. Thereafter, in step **996**, the iterator is used to return the next available stack frame element. The method name and parameter objects are then extracted from the stack frame in step **998**.

15 Having both the method name and parameter objects available, the autonomous mobile agent uses the Java reflection API’s to execute the method in step **1000**. In step **1002**, a decision point is then reached wherein a check is made to determine whether additional stack frame elements exist. If additional elements exist, then execution resumes at step **996**; conversely, execution continues at entry point **33b**, described below and illustrated in **FIG. 33**. If the restart 20 value determined in step **982** is not equal to “beginning,” execution moves on to step **984**, wherein the state of the restart variable is also evaluated. If its value is equal to “last,” execution continues at step **988**, at which point the last stack frame element is obtained. In step **990**, the method name and parameters are obtained from the stack frame object. The method is then

executed in step 992, and control continues at entry point 33b, described below. If the restart value tested in step 984 is not equal to “last,” execution continues at step 986, where a test is made to see if the restart value equals “target.” If so, execution continues with entry point 33a, described below.

5

FIG. 33 is a flowchart showing the migration and running of an autonomous agent either on the first server of its itinerary or if its execution stack is unavailable. In step 1004, execution of the target method as defined in the agent’s itinerary is initiated. In the following step, 1006, the agent executes any sub functions or tasks upon which the target method relies. The 10 intermediary results are then stored as member data within the autonomous agent in step 1008. In step 1010, the agent checks its itinerary. A decision point is then reached in step 1012, wherein the agent evaluates the itinerary to determine whether there are additional tasks to perform. If additional tasks exist, execution continues at step 1014 wherein the agent obtains the method name and formal parameters of the next function to invoke. Control then loops back to step 15 1006. If step 1012 determines that there are no more tasks to perform, processing continues at step 1018. If the agent’s itinerary indicates that the remote host was the last one to visit, then execution continues with step 1016 and the results of localized processing are transmitted to the originating host. If the agent’s itinerary indicates that it should migrate to another server, then the step 1007 is invoked, at which point an agent object is created. In step 1009, the current host 20 is removed from the list of target hosts to visit within the itinerary. Then, in step 1011, the restart value is set based upon application specific processing needs. Finally, in step 1015, a call is made to the agent’s migrate method to transport it to another remote server.

FIG. 34 is a flowchart depicting the agent collaboration subsystem of the present invention. Beginning in step **1020**, the collaborator subsystem accepts a new connection from a mobile agent. A decision point is then reached in step **1024**, where a determination is made as to whether the request is to “register.” If a positive determination is made, control passes to step **1022**, where the agent is made available for instant messaging. The agent’s availability is immediately published to all connected agents. If a negative determination is made in step **1024**, execution continues at step **1026**. At this point the collaborator checks to see if the request received is to join a conference. If it is, another decision point is reached in step **1028**, wherein the subsystem checks to see if the conference has already been established. If the conference does not exist, it is created in step **1030**. If the conference does exist, the agent will be established as a participant in step **1034**. If the request is one other than to join a conference, a check is made in step **1032** to determine if the request is to send an instant message. If it is not a request to send an instant message, processing continues to step **1036**, wherein the request is checked to see if it contains a contribution for an ongoing conference. If so, step **1040** is executed, whereby the contribution data is published to all conference participants. If step **1032** determines that the request was intended to send an instant message, the target agent’s “run as” identifier and host name or IP address are extracted from the message in step **1038**. The collaborator subsystem then checks to see if the identified mobile agent is available for chatting in step **1042**. If the agent is available, an instant message is sent to it in step **1044**. If the target agent is no longer available for a chat, then in step **1046**, a response is sent back to the requesting agent indicating that the target agent is no longer available.

Having thus described the invention in detail, it is to be understood that the foregoing description is not intended to limit the spirit and scope thereof. Accordingly, what is desired to be protected by Letters Patent is set forth in the appended claims.